Opportunities and future directions for visual soil evaluation methods in soil structure research

Guimaraes, RML; Lamande, M; Munkholm, LJ; Ball, BC; Keller, T

Published in:
Soil and Tillage Research

DOI:
10.1016/j.still.2017.01.016

First published: 21/02/2017

Document Version
Peer reviewed version

Opportunities and future directions for visual soil evaluation methods in soil structure research

Rachel M. L. Guimarães[1]*, Mathieu Lamandé[2,3], Lars J. Munkholm[2], Bruce C. Ball[4], Thomas Keller[5,6]

[1]Federal University of Technology-Paraná, Department of Agronomy, Via do Conhecimento, km 1, 85503-390, Pato Branco, PR, Brazil

[2]Aarhus University, Research Centre Foulum, Department of Agroecology, P.O. Box 50, DK-8830 Tjele, Denmark

[3]Norwegian University of Life Sciences, Faculty of Environmental Sciences and Natural Resource Management, P.O. Box 5003 NMBU, 1432 Ås, Norway

[4]Scotland's Rural College, Crop and Soil Systems Research Group, West Mains Road, Edinburgh, EH9 3JG, UK

[5]Agroscope, Department of Agroecology & Environment, Reckenholzstrasse 191, CH-8046 Zürich, Switzerland

[6]Swedish University of Agricultural Sciences, Department of Soil & Environment, Box 7014, SE-75007 Uppsala, Sweden

*Corresponding author, Tel.: +55-46-32202542

E-mail address: rachelguimaraes@utfpr.edu.br

Type of Paper: Original Research Article "SI: VSE and Compaction Res."

Abstract

As the use of visual soil evaluation (VSE) methods has spread globally, they have been exposed to different climatic and pedological scenarios, resulting in the need to elucidate limitations, encourage refinements and open up new avenues of research. The main objective of this paper is to outline the potential of VSE methods to develop novel soil structure research and how this potential could be developed and integrated within existing research. We provide a brief overview of VSE methods in order to summarize the soil information that is obtained by VSE. More detailed VSE methods could be developed to provide spatial information for soil process models, e.g. compaction models. VSE could be combined with sensing techniques at the field or landscape scale for better management of fields in the context of precision farming. Further work should be done to integrate plant vigour, roots and soil fauna into VSE methods to provide general indicators of soil quality and for estimation of environmental risk factors related to soil C storage, GHG emissions and nutrient leaching, with particular reference to temporal changes. There is a great potential in combining (rather than comparing) VSE with measurements of soil structure, i.e. integrating VSE in soil structure and compaction research, as these methods provide spatial information that is difficult to obtain with other methods.

Keywords: Soil management; Soil compaction; Sensing; Modelling; Soil quality

1. Introduction

Soil structure comprises the physical habitat of soil living organisms, and controls many important physical, chemical and biological soil functions and associated ecosystem services. Soil structure is typically defined as the spatial arrangement of soil constituents and voids (i.e. soil pores), which may also be defined as the spatial distribution of soil properties (Dexter, 1988). However, soil structure is more than just the physical arrangement of particles and pores (that was referred to as “structural form” by Kay and Angers (2001)), and includes structural stability (i.e. the ability to resist extern stresses) and structural resilience (i.e. the ability to recover upon stress removal) (Kay and Angers, 2001). Different methods can be used to evaluate the different aspects of soil structure. For example, computed tomography (CT) imaging is excellent at visualizing and quantifying the form of soil structure (for an overview, see Taina et al., 2008; Peth, 2011; Wildenshild and Sheppard, 2013) and can be used to study the dynamics of soil structural pore spaces (i.e. the dynamics of the form of soil structure) by multiple scanning as demonstrated by Peth et al. (2013), but cannot directly assess soil structure stability or resilience. Visual soil evaluation (VSE) cannot reveal as much information on the geometrical arrangement of pores and constituents as CT imaging does, but assesses both the structural form and the structural stability (e.g. DVWK, 1995a, 1997; ATV-DVWK, 2001; Boizard et al., 2007; Guimarães et al., 2011), and may reveal information on the resilience through biological indicators (e.g. Boizard et al., 2016 this issue). Unlike the texture of a soil that can be considered a static property, the soil structure is a dynamic trait. Soil structure is influenced by both natural and anthropogenic processes. The natural processes include abiotic processes induced by drying-wetting and freeze-thaw phenomena, as well as biotic processes leading to the creation of new pore spaces by the penetration of plant roots and burrowing fauna, soil aggregate stabilization by plant roots, fungi, and soil fauna (enmeshing, excretions), and soil shrinkage due to plant water uptake (Kay, 1990; Dexter, 1991; Horn et al., 1994; Horn, 2003; Hallett et al., 2013). Anthropogenic influences on soil structure are primarily related to soil management including soil tillage, soil compaction due to vehicle traffic, incorporation of organic fertilizers and amendments, as well as crop selection and fertilization (for an overview, see Kay, 1990; Bronick and Lal, 2005; Kay and Munkholm, 2011). Such aspects have significant influence on structural stability and resilience as well as structural form, all of which influence soil function (Horn, 1990; Horn et al., 1994).

Despite the recognized importance of soil structure for soil functioning, its characterization and quantification of the complex interactions (as stated above) that drive soil structure formation remain a challenge (e.g. Hallett et al., 2013; Peth et al., 2013). Visual soil evaluation (VSE) methods have been developed to assess the structural state of soil (for a review see Boizard et al. (2007)). Most VSE methods were developed as a practical diagnostic tool in agricultural extension service. Various visual methods to assess soil structure and soil quality have been developed and used for many years in different parts of the world, and these have mainly been published in reports, booklets and notes (e.g. Görbing, 1947, Peerlkamp, 1959; Preuschen, 1983; Gautronneau and Manichon, 1987; DVWK, 1995a; Shepherd, 2000; Munkholm, 2000; McKenzie, 2001; Nievergelt et al., 2002). More recently, methods have been refined, combined, and published in scientific journals (for an overview see e.g. Ball et al., 2015). In the remainder of this paper, we use 'visual soil evaluation (VSE) methods' as a general term for all methods, whereas specific methods (e.g. 'Profile Cultural'; Gautronneau and Manichon, 1987) will be referred to by their specific name. Furthermore, there has been a growing interest to (re-)use VSE methods in research, primarily have been used to characterize the impact of soil management on soil structure and to help identify the type and location of measurements for further characterisation of soil physical properties (Ball et al., 2015; this special issue).

Only a few studies have used VSE methods with regards to soil structure dynamics. Roger-Estrade et al. (2000) used the ‘Profil Cultural’ method (Gautronneau and Manichon, 1987) to quantify the temporal evolution of soil structure under contrasting tillage systems, and Boizard et al. (2013) used the same method to study recovery after compaction in a reduced tillage experiment. Ball and Munkholm (2015) showed that the ‘Visual Evaluation of Soil Structure’ (VESS) method (Guimarães et al., 2011) was able to reveal variations in soil quality and recovery, over a four-year period of evaluation, when assessing compaction by tractor and animal trampling. These authors also highlighted that repeating VSE measurements over time enables the monitoring of soil quality evolution.

All VSE methods are mainly used within an agronomic context, with the purpose of assessing soil management effects and providing soil management recommendations. Thus, it is important that VSE scores have veracity and are nearly reproducible. Therefore, soil structure is systematically evaluated according to manuals and instruction videos to reduce operator dependence for most VSE methods. In general, different operators typically find very similar scores (e.g Ball et al., 2007; Guimarães et al., 2011). Subjectivity is, however, still considered a modest limitation to VSE methods, e.g. in relation to the isolation of structural units and the assessment of their properties and efforts to further reduce this limitation continue. Other limitations include possibly confusing soil moisture effects on soil strength with those of compaction and difficulty in use in soils of extreme textures and insufficient emphasis on porosity, particularly with spade methods (Ball and Munkholm, 2015; Munkholm and Holden, 2015). Scale is also an important aspect to take account for any soil structure description method. Babel et al. (1995) proposed an initial description of soil structure (shape and surface of the structural units, geometrical arrangement, aggregate strength, bioturbation, etc.) at a given scale, and then to reproduce observations at various scales applicable across land uses and across scientific disciplines.

VSE methods yield information on the vertical thickness and depth of natural and anthropogenic soil layers, and on the spatial arrangement of structural features (profile methods) or the size distribution of soil fragments (spade methods). Such information is not available, for example, from sampling at discrete (pre-defined) depths with small volumes (e.g. undisturbed cylindrical soil cores that may have a typical volume of 100 cm^3), which are typically used in soil structure research. Several studies have demonstrated significant correlations between the various structural features (as e.g. obtained by VSE methods) and a range of soil properties (mainly soil physical properties such as, bulk density, penetration resistance, saturated hydraulic conductivity, among others; see e.g. Horn, 1990; Shepherd, 2003; Dörner and Horn, 2009; Guimarães et al., 2013; Moncada et al., 2014; Ball et al., 2016 this issue). Moreover, the shape of the fragments and an estimate of the tensile strength of the fragments is obtainable from VSE methods. The 'Profil Cultural' reports detailed information regarding the spatial arrangement and distribution of soil properties (e.g. aggregates, pores, roots, organic residues), whereas other methods such as VESS (Guimarães et al., 2011), the Visual Soil Assessment (VSA) method (Shepherd et al., 2009) and SOILpak (McKenzie et al., 1998), for example, combine this information into a score or soil quality index, either for each layer or for a whole soil profile. The reason for combining this information into a single index is that such an index will be useful for assessing the overall physical quality of a soil, for comparing soil quality across soils, and for providing soil management recommendations. However, valuable information on soil structure can be lost through the combination process. We will argue in this paper that this information could be useful in research aiming at better understanding the impact of soil structure on soil functioning (including plant growth) and better understanding of soil structure dynamics.

A joint workshop of the two ISTRO working groups on Visual Soil Examination and Evaluation (VSEE) and Subsoil Compaction held in May 2014 brought together scientists dealing with characterisation of soil structure and its dynamics with a focus on soil management impacts (soil tillage, soil degradation by compaction). A main aim of the workshop was to jointly discuss and possibly outline (i) research needs of visual soil evaluation methods, new approaches (ii) to combine VSE methods with “traditional” soil physical methods and analysis as well as with remote and proximal sensing techniques, and (iii) to integrate VSE in soil structure research for better quantification of soil structure and better understanding of soil structure dynamics caused by soil management. This article summarises and synthesizes the discussions from the workshop. Although the workshop had an emphasis on tropical conditions, most of the discussions were relevant to all soils.

The main objectives of this paper are to outline (i) research needs for improvement of VSE methods, and (ii) the opportunities of VSE methods in soil structure research. We will provide a brief overview of VSE methods, in order to summarize the soil information that is obtained by VSE. We will describe research needs for further development of VSE methods and their better integration in soil structure research. Finally, we propose ways of using and integrating the spatial information obtained by VSE in research on soil structure dynamics and soil compaction.

2. Brief overview of visual soil assessment methods

2.1 General approach of visual soil evaluation methods

Many visual soil evaluation (VSE) methods have been developed worldwide to evaluate the soil structural quality of topsoils and whole soil profiles. As mentioned above, many different methods have been developed and used in various parts of the world, but description of many methods may not be readily available for the international scientific community because they are often published in institutional reports, notes or as booklets. However, most methods share similar soil quality assessment criteria related to visible soil porosity as well as the size, shape and strength of aggregates. Please consult Boizard et al. (2007) for an overview of 10 different methods presented at the ISTRO 2005 workshop at Péronne, France. The methods generally divide into topsoil-focused spade methods and topsoil and subsoil focused profile methods. The most commonly used spade methods in research are the VSA method (Shepherd et al., 2009) and the VESS method developed from the Peerlkamp method (Ball et al., 2007; Guimarães et al., 2011) (Munkholm and Holden, 2015). Among the soil profile methods, 'Profil Cultural' (Gautronneau and Manichon, 1987; Peigné et al., 2013), SOILpak (McKenzie et al., 1998) and, most recently, the numeric visual evaluation of subsoil structure methods (SubVESS) (Ball et al., 2015) are used in research (Munkholm and Holden, 2015). These five spade and profile methods are described in detail by Batey et al. (2015). It is also important to mention methods that integrate information from different methods into an overall soil quality rating such as the Muencheberg Soil Quality Rating system (Mueller et al., 2013).

The five different VSE methods mentioned above all include assessment of size, shape and strength of soil aggregates and of visible porosity (Batey et al., 2015). These features yield information on the quality of soil as plant growth medium, habitat for soil biology and on conditions for nutrient cycling, and water and gas storage and transport. Other commonly evaluated features are soil colour (e.g. VESS, SubVESS and VSA), earthworms in terms of numbers, sizes, species and burrows (e.g. VSA and Munkholm spade method (Munkholm, 2000)), rooting in terms of proliferation and architecture, depth, and distortion (e.g. VESS, VSA, SOILpak and SubVESS), porosity (all methods) and water stable aggregates (SOILpak). Most methods include an evaluation of distinct soil layers or zones but often evaluation scores are assessed across different layers. The importance of specific evaluation of limiting layers such as hardpans is highlighted in the profile methods (SOILpak, SubVESS and 'Profil Cultural') and in some spade methods (VESS, Guimarães et al., 2011). The VSE methods differ markedly in terms of the level of details regarding the evaluation. The more detailed the analysis (as for 'Profil Cultural') the longer it takes to complete an evaluation. In general the simple spade methods such as VESS are fastest (5-15 min per sample) and the detailed profile methods take the longest time (1-3 hours) (Boizard et al., 2007; Batey et al., 2015). The fast and easy to use spade methods make it possible to do many replicates at the same time as it takes to do one detailed profile evaluation. Thereby, a larger area and more treatments can be covered within the same time interval. On the other hand this may be at the expense of more detailed understanding of specific land use or management effects on soil structure. In many cases a combination of fast and simple methods with a few more detailed evaluations may be beneficial in order to obtain both general knowledge on spatial differences and in depth knowledge of the impact of specific land use or soil management. Please consult Batey et al. (2015) for more details on similarities and differences between the commonly used methods.

2.2. Application of visual methods in practice

VSE methods are used in many countries by agricultural advisors, teachers, and farmers, even though detailed knowledge of the use of the VSE methods in practice is often lacking. More detailed VSE methods will require specialized soil knowledge for successful application, while simple spade methods only require some methodological training for successful application by students or farmers, for example. We expect that the methods are most widely used in Western Europe, Australia, New Zealand and Brazil, where most of today's known methods have been developed. To illustrate the interest in VSE methods in practice, the VESS manual has been translated into a number of languages, including Spanish, French, Portuguese, Norwegian and Danish, primarily by advisors.

2.3 Application of visual methods in soil research

The VSE methods are increasingly being used in soil research to evaluate effects of land use and soil management, primarily. Munkholm and Holden (2015) listed 29 VSE papers on arable soil and 10 VSE papers on grassland soils in a recent review and most of them had been published since 2010. In general, VSE methods have been useful to detect effects of land use and management on soil structure. Most VSE papers also include comparative quantitative soil structure data e.g. soil pore characteristics, bulk density, soil strength, soil structural stability and hydraulic conductivity. Strong correlations have been found in many cases as outlined by e.g. Batey et al. (2015). Significant correlations with crop yield have also been shown in some studies (Mueller et al., 2009; Munkholm et al., 2013).

The VSE methods have primarily been used for comparative studies where effects of land use and management has been investigated at a specific time. In a few cases the VSE methods have been applied to study soil structure dynamics, i.e. spatio-temporal changes in soil structure after e.g. animal or field traffic induced soil compaction (Ball and Munkholm, 2015; Boizard et al. 2013). Boizard et al. (2013) showed that the "Profil Cultural" was a useful tool to assess soil recovery after heavy compaction. They detected the development of a platy structure layer in the years after a heavy compaction treatment. The above mentioned studies suggest that there is a great potential for more widespread application of VSE methods in studies of soil structure dynamics. However, VSE methods are destructive by nature and this has to be taken into account when choosing VSE as a tool to study temporal evolution of soil structure, especially within field experiments.

3. Research needs for further development of visual soil assessment methods

3.1 Improving the quality of scoring by including the impact of soil moisture content at sampling

Soil aggregate fragmentation is an integral component of many visual evaluation methods (see previous section). However, fragmentation is strongly affected by the soil moisture (for an overview, see e.g. Dexter and Bird, 2001; Munkholm, 2011), and hence the soil moisture, measured in terms of water content or in terms of matric potential, at the time of assessment can influence the result of the test (Fig. 1). Water strongly affects the consistency and the strength of soil (e.g. Atterberg, 1911; Horn, 2003), consequently, a drier soil is generally harder and more difficult to break up, and therefore, extra pressure is required to fragment dry aggregates. Especially, it is important that the soil is not dried to conditions drier than it has ever experience before, as this is associated with irreversible soil structural changes, when smaller aggregates may break up due to pore weakening (Horn et al. 2014). This may not be a problem under many conditions, but could be crucial when evaluating subsoils in temperate climates. A wet soil is weak, and beyond a certain moisture content soil no longer break-up, instead the aggregates plastically deform when a pressure is applied. Both, a too dry and a too wet soil may result in a false interpretation of its structure.

Soil friability describes the tendency of a soil to break down into fragments of desired sizes upon application of a stress (Utomo and Dexter, 1981). A range of water contents can be defined within which soil friability is satisfactorily (see Munkholm, 2011). The upper (i.e. wet) limit of this range is typically defined from soil consistency and often assumed at w = PL (lower plastic limit). A shortcoming of using PL as a limit is that it is determined on remoulded soils, and natural soil may behave differently. The lower (i.e. dry) limit is less well defined but related to energy requirement for fragmentation. Soil friability is maximum at intermediate soil water contents, with the maximum friability at a water content, w, at around 0.9 × PL, see Munkholm (2011). Similarly, we can define a range of suitable water contents for visual soil evaluation (Fig. 1). It may be assumed that the range of water contents for satisfactory friability and satisfactory visual soil evaluation coincide. For this reason, it is generally recommended that visual tests are conducted while the soil is within the friable range (Ball et al., 2016 – this issue), to avoid misinterpretation of the sample. The ease of fragmenting an aggregate is one of the key factors evaluated by VESS. We suggest that the optimum range of water contents for visual soil evaluation could be investigated in future research. The range of suitable water contents may be affected by climatic conditions (e.g. rainfall patterns) and soil type (e.g. different for sand soils vs clay soils). The latter problem may be overcome by specifying a range in matric potentials rather than in water content. Another strategy could be to develop methods to normalize VSE results to a standardized water content (e.g. by using w/PL) or matric potential. This would require that the water content and/or matric potential at the time of VSE is measured, as suggested by Babel et al. (1995). Furthermore, it could be interesting to perform VSE at various water contents/potentials. We hypothesize that the change in soil quality (e.g. score) as assessed by VSE as a function of soil water status may carry some information on the resilience of a certain soil (structure).

3.2 Extending the scope of VSE by integrating biological indicators

Macrofauna and root activity, which are also assessed in VSE methods, play a major role in soil structural quality, mainly by improving macroporosity, by promoting aggregation, and by stabilizing structures (e.g. Lynch, 1984; Kay, 1990; Dexter, 1991; Uteau et al., 2013; Han et al., 2015; Pagenkemper et al., 2015). Some methods, such as the VSA, include the number of earthworms as an indicator of soil quality (Shepherd, 2009), while Munkholm (2000) uses the number of earthworm holes as another quality aspect to be evaluated. Munkholm (2000) highlights the difficulty of evaluating soil macrofauna as it can be difficult to observe the fauna before they escape the soil block extracted for evaluation. VESS does not currently include faunal presence as part of its evaluation, however, the presence of distinct biopores (resulting from earthworm and root activity) is a criterion for attributing a score and counting of earthworms within the block is proposed as an extension of the method. Franco et al. (2016, this issue) showed positive correlations between VESS and reduction in *Isoptera* and *Coleoptera* abundance, while earthworm activity has been shown to have an important impact on soil structural quality (Piron et al., 2012). Therefore, the improvement and incorporation of faunal assessments in visual methods and the evidence of their action in soil structure dynamics should be a future research goal, as also highlighted by Boizard et al. (2007) and Munkholm and Holden (2015).

3.3 Combining visual soil assessment methods with remote and proximal sensing and interactive tools for mobile devices

Remote sensing techniques can be used to show diagnostic indicators of soil properties, such as soil texture (Peng et al., 2014), organic matter content (Viscarra Rossel and Hicks, 2015; Aldan-Jague et al., 2016), organic matter quality (Ben-Dor et al., 1997), iron content, soil texture or particle size distribution, clay mineralogy, water content, soil contamination (Peng et al., 2016), cation exchange capacity and calcium carbonate content through imaging spectroscopy (Ben-Dor et al., 2009; Stenberg et al., 2010; Soriano-Disla et al., 2014) and soil moisture through RADAR sensing (Zribi et al., 2011). Estimates of these properties by means of remote sensing typically rely on relationships established from standard measurements on pre-treated and remoulded soil samples in the laboratory. However, actual in situ properties of structured soils may differ from apparent properties measured on homogenised samples. Therefore, there is a risk of misinterpretation of data. For example, Hartmann et al. (1998) showed that there is a difference in the observed cation exchange when comparing homogenized samples with in situ structured soil. Multispectral sensing can be used to estimate land cover and use, vegetation indices and degradation (Dewitte et al., 2012; Mulder et al., 2011). Here we differentiate remote sensing that is airborne or satellite based at the large scale from proximal sensing that is ground-based for finer scales (Wulf et al., 2014).

Proximal sensors utilize a variety of electromagnetic radiations to infer information on salinity, organic composition, mineralogy, moisture content, topsoil thickness and clay content (Samouelian et al., 2005; Viscarra Rossel et al., 2006). These and other sensing techniques can be used to differentiate the landscape or plot into scaled units of sensory output that can be related to site properties through field sampling (Paradelo et al., 2016). Good correlations have been observed between the results of remote or proximal sensing and soil variables such as bulk density, penetration resistance, soil organic carbon and soil moisture and, for VIS-NIR sensing of soil quality, has been related to visual quality scores for VESS (Askari et al., 2015).

A promising area of future study is the correlation of electromagnetic spectrum sensing results with visual evaluation scores as it would allow the interpolation of a limited number of Sq scores (from VESS) over the sensed areas, reducing the burden of sampling. This would be of particular relevance in precision farming where inputs are related to soil variables. Aerial photography, now available at low cost using Unmanned Aerial Vehicle (UAV/drone) technology, could be used to identify areas of compacted or degraded soil for further investigation via VSE. Combining techniques of remote and ground-based sensing and yield mapping could be used to delineate areas with similar soil properties and/or adverse yield productivity (Fig. 2), and thereby assist in selecting locations for more detailed investigation using VSE. In addition, use of handheld devices with various sensors (e.g. NIR to detect moisture content) could complement VSE and make soil quality scoring more robust (cf. Section 3.1).

Another promising area of developing technology is the use of interactive tools for mobile devices, such as smart phones and tablets, that include instructional help videos, methodologies and scoring applications, which allow field observations to be related to reference photographic guides, to make soil quality scoring more relevant or for easy transmission to experts available online. This would allow more information to be available than from a chart or field guide, reducing errors and the influence of the operator.

3.4 Integrating VSE with other properties to provide more holistic estimation of soil quality

The measurement of soil hydraulic properties is a useful indicator of a drainage or aeration limitation of the cropping potential, however, inferring these properties via visual methods can be difficult. Many soil features closely related to soil hydraulics, such as surface crusting, large cloddy structure, soil colour, surface deformation, surface ponding, soil erosion and surface microrelief can be scored visually using *ad hoc* keys (Murphy et al., 2013; Guimarães et al., 2015, Shepherd, 2009). Including surface features in visual methods could be of particular value by enabling improved inferences regarding hydraulic properties. For example, recording the presence of sealing or surface crusting or platy layers could imply restricted infiltration or water drainage. The development of visual assessments such as the erosion toolkits that relate soil texture and slope to soil structure and thereby to risk of erosion (Regan, 2012; Guimarães et al., 2015) could enable more objectivity when linking surface features with soil structural quality.

Profile methods, such as SubVESS, "Profil Cultural" and SOILpak (topsoil and subsoil) give an overall status of soil structure to a greater soil depth than the spade methods. A vertical continuous pore network is important for soil functions, such as drainage and aeration and as a conduit for root growth, all of which are key factors for crop productivity and profile methods are suitable when tracking macropore continuity (Munkholm and Holden, 2015). Identifying and distinguishing man-made from naturally compacted layers will enable profile methods to be more useful for identifying subsoil layers that require loosening. Munkholm and Holden (2015) reported that identifying the layer that limits plant growth is crucial for subsoils, therefore, reporting evaluations for individual layers is recommended by Ball et al. (2015) and McKenzie (1998).

Assessment of agricultural land in terms of soil quality and soil structure using quick VSA and VESS techniques has been shown to provide an indication of the potential for soils to store C, release GHGs and lose nutrients, and are therefore important for identifying problems as well as to combat environmental change (Cloy et al., 2015). VSA and VESS were also used to estimate the risk of soil emissions of nitrous oxide from pastures where compaction damage was present and rates of mineral N fertilizer were high. Visual assessments also have the potential to assess the risk of surface water runoff and nutrient loss. Such assessments which combine detailed soil and crop visual evaluations with fertilizer management history are areas for potential development. The potential role of soil colour was shown for the further extension of visual evaluation techniques to a soil carbon storage index. These methods show clear potential for further development and research to provide validation of scored soil and crop qualities with measured properties of soil C storage, GHG emissions and nutrient leaching (Cloy et al., 2015; Ball et al., 2016 – this issue).

Extending and combining visual methods with other simple quantitative or qualitative field methods will give a more general soil quality indicator, such as in VSA and SOILpak (Mueller et al., 2014; Munkholm and Holden, 2015). Govaerts et al. (2006) proposed a minimum data set to assess soil quality that should take into account soil and climatic conditions for the specific agro-ecological zone and their interaction with land use. Mueller et al. (2014) also proposes the combination of quantitative and qualitative field based methods with visual evaluation of soil methods. Combination of VSE methods with visual crop evaluation may also extend the agronomic relevance of VSE for identifying limiting soil conditions.

4. Potential of visual soil evaluation methods to advance soil structure research

4.1. Accounting for spatial variability in soil modelling

Quantification of the form of soil structure can be achieved through imaging (e.g. Peth et al., 2013) or indirect measurements (i.e. water and gas transport, aggregate size distribution, etc.; e.g. Ball et al., 1988). All imaging techniques and physical measurements are limited to a given size of observation, which makes our understanding of soil structure discontinuous and incomplete. Thus, extrapolation from measurements on soil samples to soil profile or to field is uncertain (e.g. Etana et al., 2013). Usually, averaged measurements on randomly sampled soil cores (10^{-2} m) are used to explain soil functioning at the profile (10^{0} m) or field scale (10^{2} m), or to parameterize models. The issue of upscaling observations at core or smaller scale to field, landscape and global scale was highlighted as one of the essential challenges for soil modelling in a recent extensive review (Vereecken et al., 2016).

The variability of a soil property can be described using probabilistic models (Perfect and Kay, 1994; Chun et al., 2008). However, simulation and evaluation of the effect of agricultural practices on soil functions often need maps of the spatial organization of the different structural features. Geophysical methods including electrical resistivity tomography, ground penetrating radar and seismic methods can be used to obtain two- or three-dimensional maps of soil physical properties that can be related to parameters relevant for soil models (Besson et al., 2004; Petersen et al., 2005). Further information on spatial variation of soil structural features can be readily assessed in situ by visual soil evaluation methods. VESS has been used to determine the minimum sampling density of VESS and of other assessments of soil quality to capture the spatial variation in a field. This involved sampling at up to 16 points per ha and mapping the data sets by kriging at decreasing sampling density to determine the optimum sampling density. This was ~0.9 – 1 per ha for the two agricultural fields assessed (Laura Thomas and Bryan Griffiths, SRUC Edinburgh, personal communication). This corroborates similar result found by Rachel M.L. Guimarães (unpublished data), who evaluated 36 blocks per ha and concluded that one VESS evaluation per ha was the minimum sample density required to accurately represent a field's soil quality via VESS, however, it is suggested that three replicates should be taken per ha for statistical purposes.

Few studies have attempted to integrate soil structure spatial variability at the profile scale as described by visual soil evaluation methods into models, but some exceptions are the studies by Benjamin et al. (1990), Coutadeur et al. (2002) and Ndiaye et al. (2007). The methodology was the same for all these studies: physical measurements were performed in the laboratory or in the field for the different structural zones as identified on the soil profile by VSE, and measured soil parameters were used to model heat or water transport in two dimensions. However, none of these works took into account the temporal variation in soil structure, which would need also a model of structure dynamics, e.g. ‘Sisol’ developed by Roger-Estrade et al. (2009). For the studies mentioned above, VSE methods were used to give information on the spatial distribution of different zones, but soil properties needed to model the process in question (e.g. water transport) were obtained by measurements. VSE methods were used to choose the position of the sampling, which might lead to an overestimation of the differences between, for example, loose and compacted zones, as transitions between these zones might be difficult to sample.

In a recent study, Moncada et al. (2014) showed that pedotransfer functions could benefit from integrating a VSE score. Similarly, it was shown in the DVWK bulletins 234 and 235 (DVWK 1995b, 1997) that prediction of soil functions (e.g. soil strength) requires knowledge of in situ soil structural features related to aggregation, in addition to intrinsic soil properties (e.g. texture). All these results might be due to the more holistic approach of VSE methods as compared with specific physical measurements. It is well known that soil structure changes over time due to natural and antrophogenic factors. Despite of this, dynamic changes in soil structure is ignored in most soil models (Vereecken et al., 2016) –

most likely due to lack of empirical data. VSE methods are sensitive to temporal changes (Boizard et al., 2013; Ball and Munkholm, 2015) and may be used as tool to assess in situ changes at aggregate to pedon scale and at different depths. Qualitative information from a VSE method at different times before and after tillage could be successfully used to model soil structural dynamics as affected by tillage (Roger-Estrade et al., 2000). Fig. 3 illustrates how the spatial information obtained from visual soil evaluation could be used in soil process modelling. The qualitative information from VSE may be supplemented with quantitative data at selected times and depths, which may be used in more mechanistic soil modelling.

4.2. Improving the description of compaction propagation by including spatial description of soil structure within the soil profile

Compaction is a major soil threat due to ongoing intensification of agricultural practices: farmers and contractors choose large machinery to increase efficiency of field operations, and industry designs machinery that can perform on weak soils to increase flexibility of field operations planning (Schjønning et al., 2015). Description of the stress-strain processes during compaction of agricultural soils is typically based on geotechnical frameworks using continuum mechanics (Nawaz et al., 2013). However, agricultural soils present a three-dimensional organization of various components (mineral and organic particles, plant residues, stones) (e.g. Horn, 1990). Although approaches from continuum mechanics have been shown to produce fairly good estimations of stress transmission in arable soil (Keller et al., 2014), especially tilled topsoils may rather resemble a granular material (assembly of aggregates) than a continuum. Horn (1990) showed that stress transmission is affected by soil aggregation, readily assessed in some VSE techniques. The model described and applied by Richards et al. (1997) and Richards and Peth (2009) could accommodate heterogeneity of soil properties and accounts for their evolution due to mechanical and hydraulic stresses. Naveed et al. (2016) recently observed that, in topsoils, stress propagation was heterogeneous and occurred through specific paths as long as the macro-structures were not deformed (Fig. 4). Thus, mechanics of tilled soil layers may be better described by granular matter physics than continuum physics. The mechanical behaviour of granular materials largely depends on grain size distribution (Voivret et al., 2007) and grain shapes (Azéma et al., 2009). By analogy, soil aggregate size distribution and aggregate shapes are expected to influence soil mechanical behaviour. Fig. 5a illustrates the elastic mode of stress propagation under a point load in an isotropic and continuous matter as described by Boussinesq (1885), which might be enough to describe stress propagation under certain soil conditions. Bulk measurements of soil physical parameters (such as measurements on soil cores) average soil properties for the volume of the sample, and measurements on replicated soil samples are typically averaged to represent properties at the pedon scale. Using average soil properties for a collection of aggregates may lead to an oversimplified description of soil properties within a profile that would result in an unrealistic stress propagation (Fig. 5b). Introducing some information about the aggregate properties (size distribution) and how the collection of aggregates is spatially organized would improve description of stress propagation and therefore help better understanding mechanical behaviour of structured soil (Fig. 5c). Therefore, information from VSE methods associated with granular physics would help to better understand stress-strain relationships of aggregated soil layers.

5. Conclusions

Since their inception VSE methods have grown to become important tools in research. However, VSE methods still need better harmonization and reduction in subjectivity in aggregate exposure and the influence of soil moisture content at sampling for more accurate scoring. Handheld sensors and ICT devices may also help in this area. The spatial distribution of structural features recorded by VSE methods is often integrated into a score or soil quality index. We argue that VSE provides important information regarding spatial distribution of soil structure, particularly aggregation and macro-porosity, which could be disaggregated and used to better understand various soil processes, especially the process of soil compaction. More detailed VSE methods, such as 'Profil Cultural', could be developed (simplified, disaggregated and made more accessible) so that the spatial information is more easily provided. VSE could be combined with sensing techniques at field or landscape scale for better management of fields in the context of precision farming. Combining VSE methods with visual crop evaluation may extend the agronomic relevance of VSE for identifying limiting soil conditions. Further work should be done to integrate plant vigour, roots and soil fauna into VSE methods to provide general indicators of soil quality and environmental indicators of greenhouse gas emission, carbon storage and nutrient transport. For this purpose more comparisons between scoring and field/laboratory measurements are needed. However, we see a great potential in combining (rather than comparing) VSE with measurements of soil structure, i.e. integrating VSE in soil structure research, as these methods provide repeatable spatial information on large-scale aspects of soil structure that are difficult to obtain with other methods.

Acknowledgements

This paper is an output from the workshop on *Soil structural quality of tropical soils: Visual evaluation methods and soil compaction prevention strategies* that was held 26-30 May 2014 in Maringá, Paraná, Brazil. The workshop was financially supported by the International Soil Tillage Research Organization (ISTRO), which is gratefully acknowledged. The workshop was organized as a joint meeting of the ISTRO working groups on Visual Soil Examination and Evaluation (VSEE) and on Subsoil Compaction. LJM would like to acknowledge support from the Danish Ministry of Environment and Food through the OptiPlant project. BCB would like to acknowledge financial Support from the Rural & Environment Science & Analytical Services Division of the Scottish Government (R033003). ML and TK gratefully acknowledge financial support from the Danish Research Council for Technology and Production Sciences (Project No. 11-106471 "StressSoil"). RMLG would like to acknowledge Dr. Craig D. Rogers for providing photographs for Fig. 2.

References

Aldana-Jague, E., Heckrath, G., Macdonald, A., van Wesemael, B., Van Oost, K., 2016. UAS-based soil carbon mapping using VIS-NIR (480-100 nm) multi-spectral imaging: potential and limitations. Geoderma 275, 55-66.

Askari, M.S., Cui, J., O'Rourke, S.M., Holden, N.M., 2015. Evaluation of soil structural quality using VIS-NIR spectra. Soil Till. Res., 134, 1-10

Atterberg, A., 1911. Über die physikalische Bodenuntersuchung und über die Plastizität der Tone. Internationale Mitteilungen für Bodenkunde 1, 10-43.

ATV-DVWK, 2001. Gefügestabilität ackerbaulich genutzter Mineralböden Teil III: Methoden für eine nachhaltige Bodenbewirtschaftung, ATV-DVWK-M 901 (ISBN-10: 3935669704), 27 p.

Azéma, E., Radjai F., Saussine, G., 2009. Quasistatic rheology, force transmission and fabric properties of a packing of irregular polyhedral particles. Mech. Mater. 41, 729-741.

Babel, U., Benecke, P., Hartge, K.H., Horn, R., Wiechmann, H., 1995. Determination of soil structure at various scales. In: Hartge, K.H., Stewart, B.A. (Eds.), Soil Structure – its Development and Function. Advances in Soil Science, CRC Press, ISBN: 1-56670-173-2, pp. 1-10.

Ball, B.C., Batey, T., Munkholm, L.J., 2007. Field assessment of soil structural quality - a development of the Peerlkamp test. Soil Use Manage. 23, 329-337.

Ball, B.C., Batey, T., Munkholm, L.J., Guimarães, R.M.L., Boizard, H., McKenzie, D.C., Peigné, J., Tormena, C.A., Hargreaves, P., 2015. The numeric visual evaluation of subsoil structure (SubVESS) under agricultural production. Soil Till. Res. 148, 85-96.

Ball, B.C., Guimarães, R.M.L, Cloy, J.M., Hargreaves, P., Shepherd., T.G., McKenzie, B.M., 2016. Visual soil evaluation: a summary of some applications and potential developments for agriculture. Soil Till. Res. (This issue).

Ball, B.C., Munkholm, L.J., 2015. The expanding discipline and role of visual soil evaluation. In: Ball, B.C., Munkholm, L.J. (Eds.), Visual Soil Evaluation: Realizing Potential Crop Production with Minimum Environmental Impact. CAB International, Wallingford, pp. 142-154.

Ball, B.C., Munkholm, L.J., Batey, T. (Eds.), 2012. Applications of visual soil evaluation. Soil Till. Res. 127, 1-99.

Ball, B.C., O'Sullivan, M.F., Hunter, R., 1988. Gas diffusion, fluid flow and derived pore continuity indices in relation to vehicle traffic and tillage. J. Soil Sci. 39, 327-339.

Batey, T., Guimarães, R.M., Peigné, J., Boizard, H., Ball, B., Munkholm, L., 2015. Assessing Structural Quality for Crop Performance and for Agronomy (VESS, VSA, SOILpak, Profil Cultural, SubVESS). In: Ball, B.C., Munkholm, L.J. (Eds.), Visual Soil Evaluation: Realizing Potential Crop Production with Minimum Environmental Impact. CAB International, Wallingford, pp. 15-30.

Ben-Dor, E., Chabrillat, S., Demattê, J.A.M., Taylor, G.R., Hill, J., Whiting, M.L., Sommer, S. 2009. Using Imaging Spectroscopy to study soil properties. Remote Sens. Environ. 113, 38-S55.

Ben-Dor, E., Inbar, Y., Chen, Y., 1997. The reflectance spectra of organic matter in the visible near-infrared and short wave infrared region (400-2500 nm) during a controlled decomposition process. Remote Sens. Environ. 61, 1-15.

Benjamin, J.G., Blaylock, A.D., Brown, H.J., Cruse, R.M., 1990. Ridge tillage effects on simulated water and heat transport. Soil Till. Res. 18, 167-180.

Besson, A., Cousin, I., Samouëlian, A., Boizard, H., Richard, G., 2004. Structural heterogeneity of the soil tilled layer as characterized by 2D electrical resistivity surveying. Soil Till. Res. 79, 239-249.

Boizard, H., Batey, T., McKenzie, D.C., Richard, G., Roger-Estrade, J., Ball, B.C., Bradley, I., Cattle, S., Hasinger, G., Munkholm, L.J., Niewergelt, J., Peigné, J., Shepherd, G., 2007. Field meeting "Visual Soil Structure Assessment" held at the INRA Research Station, Estrées-Mons, France, 25-2 May 2005, 34 pp.

Boizard, H., Peigné, J., Sasal, M.C., Guimarães, M.F., Piron, D., Tomis, V., Vian, J.F., Cadoux, S., Ralisch R., Tavares Filho, J., Heddadj, D., Battista, J., Duparque, A., Franchini, J.C., Roger-Estrade, J., 2016. Developments in the “profil cultural” method for an improved assessment of soil structure under no-till. Soil Till. Res. (This issue).

Boizard, H., Yoon, S.W., Leonard, J., Lheureux, S., Cousin, I., Roger-Estrade, J., Richard, G., 2013. Using a morphological approach to evaluate the effect of traffic and weather conditions on the structure of a loamy soil in reduced tillage. Soil Till. Res. 127, 26-33.

Boussinesq, J., 1885. Application des Potentiels à l’étude de l’équilibre et du Mouvement des Solides Élastiques. Gauthier-Villars, Paris, pp. 30.

Bronick, C.J., Lal, R., 2005. Soil structure and management: a review. Geoderma 124, 3-22.

Chun, H.C., Gimenez, D., Yoon, S.W., 2008. Morphology, lacunarity and entropy of intra-aggregate pores: Aggregate size and soil management effects. Geoderma 146, 83-93.

Cloy, J.M., Ball, B.C., Shepherd, T.G., 2015. Evaluating land quality for carbon storage, greenhouse gas emissions and nutrient leaching. In: Ball, B.C., Munkholm, L. R. (Eds), Visual Soil Evaluation: Realising Potential Crop Production with Minimum Environmental Impact. CABI, Wallingford, UK, pp. 103-121.

Coutadeur, C., Coquet, Y., Roger-Estrade, J., 2002. Variation of hydraulic conductivity in a tilled soil. Eur. J. Soil Sci. 53, 1-10.

Dewitte, O., Jones, A., Elbelrhiti, H., Hor ion, S., Montanarella, L., 2012. Satellite remote sensing for soil mapping in Africa: An overview. Prog. Phys. Geogr. 36, 514 -538.

Dexter, A.R., 1991. Amelioration of soil by natural processes. Soil Till. Res. 20, 87-100.

Dexter, A.R., Bird, N.R.A., 2001. Methods for predicting the optimum and the range of soil water contents for tillage based on the water retention curve. Soil Till. Res. 57, 203-212.

Dörner, J., Horn, R., 2009. Direction-dependent behaviour of hydraulic and mechanical properties in structured soils under conventional and conservation tillage. Soil Till. Res. 102, 225-232.

DVWK, 1995a. Bodenkundliche Untersuchungen im Felde zur Ermittlung von Kennwerten zur Standortcharakterisierung. Teil I: Ansprache der Böden. DVWK-Regel 129/1995 (ISBN 3-89554-024-2).

DVWK, 1995b. Gefügestabilität ackerbaulich genutzter Mineralböden. Teil 1: Mechanische Belastbarkeit. DVWK Merkblatt 234, ATV-DVWK, Hennef.

DVWK, 1997. Gefügestabilität ackerbaulich genutzter Mineralböden. Teil 2: Auflastabhängige Veränderung von bodenphysikalischen Kennwerten. DVWK Merkblatt 235, ATV-DVWK, Hennef.

DVWK, 1999. Bodenkundliche Untersuchungen im Felde zur Ermittlung von Kennwerten zur Standortcharakterisierung. Teil II: Ableitungen zu Wasser- und Lufthaushalt von Böden. DVWK-Regel 136/1999 (ISBN 3-935067-55-0).

Etana, A., Larsbo, M., Keller, T., Arvidsson, J., Schjønning, P., Forkman, J., Jarvis, N., 2013. Persistent subsoil compaction and its effects on preferential flow patterns in a loamy till soil. Geoderma 192, 430-436.

Franco, A.L.C., Cherubin, M.R., Cerri, C.E.P., Guimarães, R.M.L., Cerri, C.C., 2016. Relating the visual soil structure status and the abundance of soil engineering invertebrates across land use change. Soil Till. Res. (This issue).

Gautronneau, Y., Manichon, H., 1987. Guide méthodique du profil cultural. GEARA et CEREF, 1987. Mimeografado.

Görbing, J. 1947. Die Grundlagen der Gare im praktischen Ackerbau (Band I und II), Landbuch Verlag GMBH, Hannover.

Govaerts, B., Sayre, K., Deckers, J., 2006. A minimum data set for soil quality assessment of wheat and maize cropping in the highlands of Mexico. Soil Till. Res. 87, 163–174.

Guimarães, R.M.L., Ball, B.C., Tormena, C.A., 2011. Improvements in the visual evaluation of soil structure. Soil Use Manage. 27, 395-403.

Guimarães, R.M.L., Ball, B.C., Tormena, C.A., Giarola, N.F.B., da Silva, A.P., 2013. Relating visual evaluation of soil structure to other physical properties in soils of contrasting texture and management. Soil Till. Res. 127, 92–99.

Guimarães, R.M.L., Fenton, O., Murphy, B., Tormena, C.A., 2015. Soil structure under adverse weather/climate conditions. In: Ball, B.C., Munkholm, L.J. (Eds.), Visual Soil Evaluation: Realizing Potential Crop Production with Minimum Environmental Impact. CAB International, Wallingford, pp. 15-30.

Hallett, P.D., Karim, K.H., Bengough, A.G., Otten, W., 2013. Biophysics of the vadose zone: from reality to model systems and back again. Vadose Zone J. 12, doi:10.2136/vzj2013.05.0090.

Han, E., Kautz, T., Perkons, U., Uteau, D., Peth, S., Huang, N., Horn, R., Köpke, U., 2015. Root growth dynamics inside and outside of soil biopores as affected by crop sequence determined with the profile wall method. Biol. Fertil. Soils 51, 847-856.

Hartmann, A., Gräsle, W., Horn, R.,1998. Cation exchange processes in structured soils at various hydraulic properties. Soil Till. Res. 47,67-72.

Horn R., Taubner H., Wuttke M., Baumgartl, T. 1994. Soil physical properties and processes related to soil structure. Soil Till. Res. 30, 187-216.

Horn, R. 2003. Stress–strain effects in structured unsaturated soils on coupled mechanical and hydraulic processes. Geoderma 116, 77-88.

Horn, R., 1990. Aggregate characterization as compared to soil bulk properties. Soil Till. Res. 17, 265-289.

Horn R., Peng X., Fleige H. & Dörner J. 2014. Pore rigidity in structured soils—only a theoretical boundary condition for hydraulic properties? Soil Sci. Plant Nutr. 60, 3-14.

Kautz, T., Amelung, W., Ewert, F., Gaiser, T., Horn, R., Jahn, R., Javaux, M., Kemna, A., Kuzyakov, Y., Munch, J., Pätzold, S., Peth, S., Scherer, H., Schloter, M., Schneider, H., Vanderborght, J., Vetterlein, D., Walter, A., Wiesenberg, G., Köpke, U., 2013. Nutrient acquisition from arable subsoils in temperate climates: a review. Soil Biol. Biochem. 57, 1003-1022.

Kay, B.D., Angers, D.A., 2001. Soil structure. In: Sumner, M. E. (Ed.), Handbook of Soil Science. CRC Press, Boca Raton. p. 229-276.

Kay, B.V., 1990. Rates of change of soil structure under different cropping systems. Adv. Soil Sci. 12, 1-52.

Kay, B.V., Munkholm, L.J., 2011. Managing the Interactions between Soil Biota and their Physical Habitat in Agroecosystems. In: Ritz, K., Young, I. (Eds.), The Architecture and Biology of Soils: Life in Inner Space, CAB International, pp. 170-195.

Keller, T., Lamandé, M., Arvidsson, J., Berli, M., Ruiz, S., Schjønning, P., Selvadurai A.P.S., 2014. Transmission of vertical soil stress under agricultural tyres: comparing measurements with simulations. Soil Till. Res. 140, 106-117.

Kramer, L.F.M. , Tormena, C.A., Guimarães, R.M.L., Muller, M.M.L., Michalovicz, L., Moreira, W.H., 2015. Avaliação qualitativa e quantitativa da qualidade estrutural do solo em mata nativa e sob cultivo. In: IV Reunião Paranaense de Ciência do Solo, 2015, Cascavel (Conference abstract).

Lynch, J.M., 1984. Interactions between biological processes, cultivation and soil structure. Plant Soil 76, 307-318.

McKenzie, D., 1998. SOILpak for cotton growers, 3rd Edition. Orange, New South Wales, Australia.

McKenzie, D.C., 2001. Rapid assessment of soil compaction damage, I. The SOILpak score, a semi-quantitative measure of soil structural form. Austr. J. Soil Res. 39, 117-125.

Moncada, M.P., Penning, L.H., Timm, L.C., Gabriels, D., Cornelis, W.M., 2014. Visual examinations and soil physical and hydraulic properties for assessing soil structural quality of soils with contrasting textures and land uses. Soil Till. Res. 140, 20-28.

Mueller, L., Kay, B.D., Hu, C., Li, Y., Schindler, U., Behrendt, A., Shepherd, T.G., Ball, B.C., 2009. Visual assessment of soil structure: evaluation of methodologies on sites in Canada, China and Germany. Part I: Comparing visual methods and linking them with soil physical data and grain yield of cereals. Soil Till. Res. 103, 178–187.

Mueller, L., Saparov, A., Lischeid, G., 2014. Novel Management and Assessment Tools for Monitoring and Management of Land and Water Resources in Agricultural Landscapes of Central Asia. Springer International, Switzerland, pp.115-142.

Mueller, L., Shepherd, G., Schindler, U., Ball, B.C., Munkholm, L.J., Hennings, V., Smolentseva, E., Rukhovic, O., Lukin, S., Hu, C., 2013. Evaluation of soil structure in the framework of an overall soil quality rating. Soil Till. Res. 127, 74-84.

Mulder, V. L., deBruin, S., Schaepman, M. E., Mayr, T.R., 2011. The use of remote sensing in soil and terrain mapping - A review. Geoderma 162, 1 -19.

Munkholm, L.J., 2000. The spade analysis - a modification of the qualitative spade diagnosis for scientific use, Tjele, Denmark, pp. 1-40.

Munkholm, L.J., 2011. Soil friability: A review of the concept, assessment and effects of soil properties and management. Geoderma 167-168, 236-246.

Munkholm, L.J., Heck, R.J., Deen, B., 2013. Long-term rotation and tillage effects on soil structure and crop yield. Soil Till. Res. 127, 85–91

Munkholm, L.J., Holden, N.M., 2015. Visual evaluation of grassland and arable management impacts on soil quality. In: Ball, B.C., Munkholm, L.J. (Eds.), Visual Soil Evaluation: Realizing Potential Crop Production with Minimum Environmental Impact. CAB International, Wallingford, pp. 49-65.

Murphy, B.W., Crawford, M.H., Duncan, D.A., McKenzie, D.C., Koen, T.B., 2013. The use of visual soil assessment schemes to evaluate surface structure in a soil monitoring program. Soil Till. Res. 127, 3-12.

Naderi-Boldaji, M., Sharifi, A., Hemmat, A., Alimardani, R., Keller, T., 2014. Feasibility study on the potential of electrical conductivity sensor Veris® 3100 for field mapping of topsoil strength. Biosyst. Eng. 126, 1-11.

Naveed, M., Schjønning, P., Keller, T., de Jonge, L.W., Moldrup, P., Lamandé, M., 2016. Quantifying vertical stress transmission and compaction-induced soil structure using sensor mat and X-ray computed tomography. Soil Till. Res. 158, 110-122.

Nawaz, M.F., Bourrié, G., Trolard, F., 2013. Soil compaction impact and modelling. A review. Agron. Sust. Dev. 33, 291–309.

Ndiaye, B., Molénat, J., Hallaire, V., Gascuel, C., Hamon, Y., 2007. Effects of agricultural practices on hydraulic properties and water movement in soils in Brittany (France). Soil Till. Res. 93, 251-263.

Nievergelt, J., Petrasek, M., Weisskopf, P., 2002. Bodengefüge: Ansprechen und Beurteilen mit visuallen Mitteln. Schriftenreihe der FAL 41 (ISBN 3-905608-62-6), 94 p.

Pagenkemper, S.K., Athmann, M., Uteau, D., Kautz, T., Peth, S., Horn, R. 2015. The effect of earthworm activity on soil bioporosity – Investigated with X-ray computed tomography and endoscopy. Soil Till. Res. 146 A, 79-88.

Paradelo, M., Hermansen C., Knadel, M., Moldrup, P., Greve, M.H., de Jonge, L.W., 2016. Field-scale predictions of soil contaminant sorption using visible-near infrared spectroscopy. J. Near Infrared Spectrosc. 24, 281-291.

Peerlkamp, P.K., 1959. A visual method of soil structure evaluation. Meded. v.d. Landbouwhogeschool en Opzoekingsstations van de Staat te Gent. XXIV No. 24, pp. 216-221.

Peigné, J., Vian, J.F., Cannavacciuolo, M., Lefevre, V., Gautronneau, Y., Boizard, H., 2013. Assessment of soil structure in the transition layer between topsoil and subsoil using the profil cultural method. Soil Till. Res. 127, 13-25.

Peng, Y., Bou Kheir, R., Adhikari, K., Malinowski, R., Greve, M.B., Knadel, Greve, M.H., 2016. Digital mapping of toxic metals in Qatari soils using remote sensing and ancillary data. Remote Sensing 8, 1003.

Peng, Y., Knadel, M., Gislum, R., Schelde, K., Thomsen, A., Greve, M.H., 2014. Quantification of SOC and clay content using visible near-infrared reflectance-mid-infrared reflectance spectroscopy with Jack-Knifing partial squares regression. Soil Sci. 179, 325-332.

Perfect, E., Kay, B.D., 1994. Statistical characterization of dry aggregate strength using rupture energy. Soil Sci. Soc. Am. J. 58, 1804-1809.

Petersen, H., Rabbel, W., Horn, R., Fleige, H., 2005. Applicability of geophysical prospecting methods for mapping of soil compaction and variability of soil texture on farm land. J. Plant Nutr. Soil Sci. 168, 1-12.

Peth, S., 2011. Noninvasive quantification of 3D pore space structures in soils. In: Glinski, J., Horabik, J., Lipiec, J. (Eds.), Encyclopedia of Agrophysics. Springer, Berlin, pp. 516-519.

Peth, S., Nellesen, J., Fischer, G., Tillmann, W., Horn R., 2013. Dynamics of Soil Macropore Networks in Response to Hydraulic and Mechanical Stresses Investigated by X-ray Microtomography. In: Logsdon, S., Horn, R., Berli, M. (Eds.), Advances in Agricultural Systems Modeling 3. Quantifying and Modeling Soil Structure Dynamics. pp. 121-153.

Piron, D., Pérès, G., Hallaire, V., Cluzeau, D., 2012. Morphological description of soil structure patterns produced by earthworm bioturbation at the profile scale. Eur. J. Soil Biol. 50, 83–90.

Preuschen, G. 1983. Die Spatendiagnose und ihre Auswertung. In: Root ecology and its pracitical application. eds W. Böhm, L. Kutschera & E. Lichtenegger), International Symposium Gumpenstein, 1982, Bundesanstalt Gumpenstein, A-8952 Irdning, pp. 355-368.

Regan, J.T., 2012. The erodibility and surface runoff potential of a selection of Irish tillage soils. PhD Thesis, National University of Ireland, Galway, Ireland.

Richards, B.G., Baumgartl, T., Horn, R., Gräsle, W. 1997. Modelling the effects of repeated wheel loads on soil profiles. Int. Agrophys. 11, 177-187.

Richards, B.G., Peth, S. 2009. Modelling soil physical behaviour with particular reference to soil science. Soil Till. Res. 102, 216-224.

Roger-Estrade, J., Richard, G., Boizard, H., Boiffin, J., Caneill, J., Manichon, H., 2000. Modelling changes in the tilled layer structure over time as a function of cropping systems. Eur. J. Soil Sci. 51, 455-474.

Roger-Estrade, J., Richard, G., Dexter, A.R., Boizard, H., De Tourdonnet, S., Bertrand, M., Caneill, J., 2009. Integration of soil structure variation with time and space into models for crop management. A review. Agron. Sustain. Dev. 29, 135-142.

Samouelian, A., Cousin, I., Tabbagh, A., Bruand, A., Richard, G., 2005. Electrical resistivity survey in soil science: a review. Soil Till. Res. 83, 173 -193.

Schjønning, P., Lamandé, M., Munkholm, L.J., Lyngvig, H.S., 2016. Soil precompression stress, penetration resistance and crop yields in relation to differently-trafficked, temperate-region sandy loam soils. Soil Till. Res. 16, 298-308.

Schjønning, P., van den Akker, J.J.H., Keller, T., Greve, M.H., Lamandé, M., Simojoki, A., Stettler, M., Arvidsson, J., Breuning-Madsen, H., 2015. Driver-Pressure-State-Impact-Response (DPSIR) analysis and risk assessment for soil compaction – a European perspective. Adv. Agron. 133, 183-237.

Shepherd, T.G., 2000. Visual soil assessment. Field Guide for Cropping and Pastoral Grazing on Flat to Rolling Country, 1st edition, 1. horizons.mw & Landcare Research, Palmerston North, New Zealand.

Shepherd, T.G., 2003. Assessing soil quality using visual soil assessment. In: Currie, L.D., Hanly, J.A. (Eds.), Tools for Nutrients and Pollutant Management: Applications to Agriculture and Environmental Quality. Occasional Report No. 17. Fertilizer and Lime Research Centre, Massey University, Palmerston North, pp. 153–166.

Shepherd, T.G., 2009. Visual soil assessment. Volume 1. Field guide for pastoral grazing and cropping on flat to rolling country. Second edition, Horizons Research Council, Palmerston North, New Zealand, pp. 120.

Soane, B.D., van Ouwerkerk, C. (Eds.), 1994. Soil compaction in crop production. Developments in Agricultural Engineering 11, 662 + xvii p.

Soriano-Disla, J.M., Janik, L.J., Viscarra Rossel, R.A., Macdonald, L.M., McLaughlin, M.J., 2014. The performance of visible, near-, and mid-infrared reflectance spectroscopy for prediction of soil physical, chemical, and biological properties. Appl. Spectrosc. Rev. 49, 139-186.

Stenberg, B., Viscarra Rossel, R.A., Mouazen, A.M., Wetterlind, J., 2010. Visible and near infrared spectroscopy in soil science. Adv. Agron. 107, 163-215.

Taina, I. A., Heck, R.J., Elliot, T.R., 2008. Application of X-ray computed tomography to soil science: A literature review. Can. J. Soil Sci. 88, 1-20.

Uteau, D., Pagenkemper, S.K., Peth, S., Horn, R., 2013. Root and time dependent soil structure formation and its influence on gas transport in the subsoil. Soil Till. Res. 132, 69-76.

Utomo, W.H., Dexter, A.R., 1981. Soil Friability. J. Soil Sci. 32, 203-213.

Vereecken, H., Schnepf, A., Hopmans, J. W., Javaux, M., Or, D., Roose, T., Vanderborght, J., Young, M. H., Amelung, W., Aitkenhead, M., Allison, S. D., Assouline, S., Baveye, P., Berli, M., Brüggemann, N., Finke, P., Flury, M., Gaiser, T., Govers, G., Ghezzehei, T., Hallett, P., Hendricks Franssen, H. J., Heppell, J., Horn, R., Huisman, J. A., Jacques, D., Jonard, F., Kollet, S., Lafolie, F., Lamorski, K., Leitner, D., McBratney, A., Minasny, B., Montzka, C., Nowak, W., Pachepsky, Y., Padarian, J., Romano, N., Roth, K., Rothfuss, Y., Rowe, E. C., Schwen, A., Šimůnek, J., Tiktak, A., Van Dam, J., van der Zee, S. E. A. T. M., Vogel, H. J., Vrugt, J. A., Wöhling, T. & Young, I. M. 2016. Modeling Soil Processes: Review, Key Challenges, and New Perspectives. Vadose Zone J., 15. doi:10.2136/vzj2015.09.0131

Viscarra Rossel, R.A., Walvoort, D.J.J., McBratney, A.B., Janik, L.J., Skjemstad, J.O., 2006. Visible, near infrared, mid infrared or combined diffuse reflectance spectroscopy for simultaneous assessment of various soil properties. Geoderma, 131, 59-75.

Voivret, C., Radjai, F., Delenne, J.-Y., El Youssoufi, M.S., 2007. Space-filling properties of polydisperse granular media. Phys. Rev. E 76, 021301.

Wildenshild, D., Sheppard, A.P., 2013. X-ray imaging and analysis techniques for quantifying pore-scale structure and processes in subsurface porous medium systems. Adv. Water Resour. 51, 217-246.

Wulf, H., Mulder, T., Schaepman, M. E., Keller, A., Jörg P., 2015. Remote Sensing of Soil: project report from the Federal Office of the Environment (FOEN/BAFU). University of Zurich. Avaiable at: http://www.geo.uzh.ch/fileadmin/files/content/abteilungen/rsl1/Remote_sensing_of_soils_BAFU_report_dpi300_v.pdf (assessed 28.04.2016).

Zribi, M., Baghdadi, N., Nolin, M., 2011. Remote Sensing of Soil. Appl Environ Soil Sci. 2p.

Figure captions

Fig. 1. Schematic illustration of the suitable range of soil water contents for visual soil evaluation, in analogy to the relationship between soil friability and soil water content. Adapted from Munkholm (2011).

Fig. 2. Conceptual figure showing the use of remote and proximal sensing and interactive tools for mobile devices together with visual soil evaluation. Remote sensing and ground-based sensing can identify variations in soil properties and yield-limiting factors (e.g. soil texture, nitrogen availability, soil moisture, soil compaction), while yield mapping reflects the spatial variability of productivity. For example, combining areas of poor soil conditions and restricted productivity reveals zones that require further evaluation by VSE in order to deduce specified soil management recommendations for soil improvement. Ground-based sensing photo from Naderi-Boldaji et al. (2014). Visual soil evaluation photo from Dr. Craig D. Rogers

Fig. 3. Conceptual figure illustrating how the spatial information obtained from visual soil evaluation could be used in soil process modelling. We outline two ways of incorporating structural information in models, either via localization of areas of different soil properties (left) or via a statistical approach (right). Detailed profile methods can be used for either method, while spade methods are limited to incorporation of spatial information via statistical means. Different levels of grey in the lower left picture represent different soil quality scores or different values of a given soil property. Profil Cultural photo from Boizard et al., (2017 this issue). VESS photo from Rachel M.L. Guimarães.

Fig. 4. The importance of including structure information for predicting stress propagation. Stress transmission in an undisturbed soil column (0.2 m high and 0.2 m in diameter) derived from X-ray computed tomography at applied stresses of 275 kPa (A) and 620 kPa (B). *Source*: from Naveed et al. (2016).

Fig. 5. Spatial information on soil structure provided by VSE could potentially lead to a better representation of stress propagation. (A) is a photoelastic view of a plate, (B) a regular packing of mono-sized discs and a (C) is a random packing of discs with three different sizes. All are subjected to a point load of 600 N. The plate and the discs were made of polycarbonate, which has a Young's modulus of 2.0 GPa and a Poisson's ratio of 0.37.

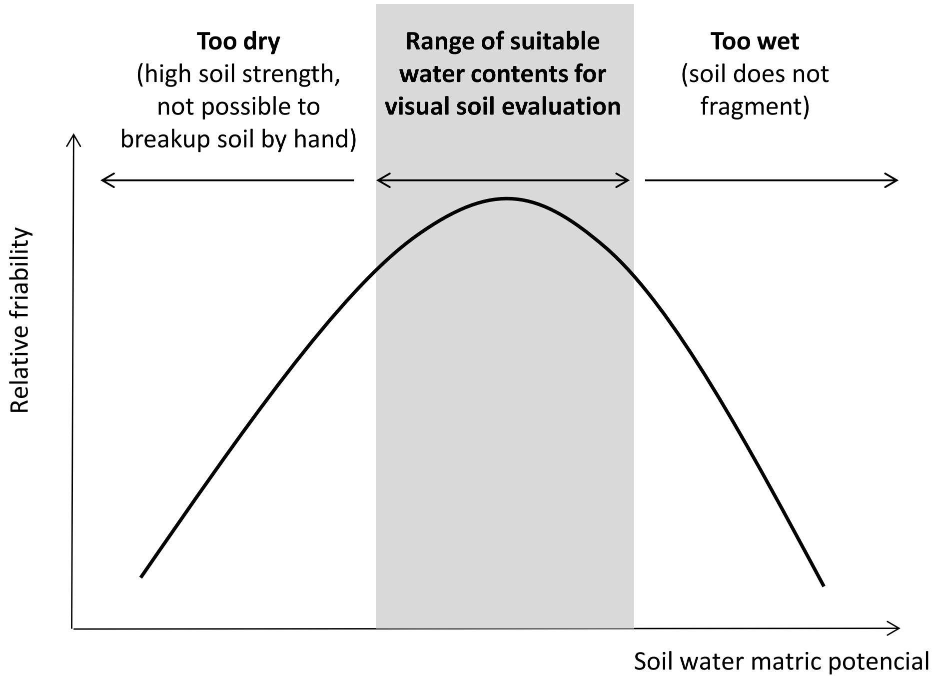
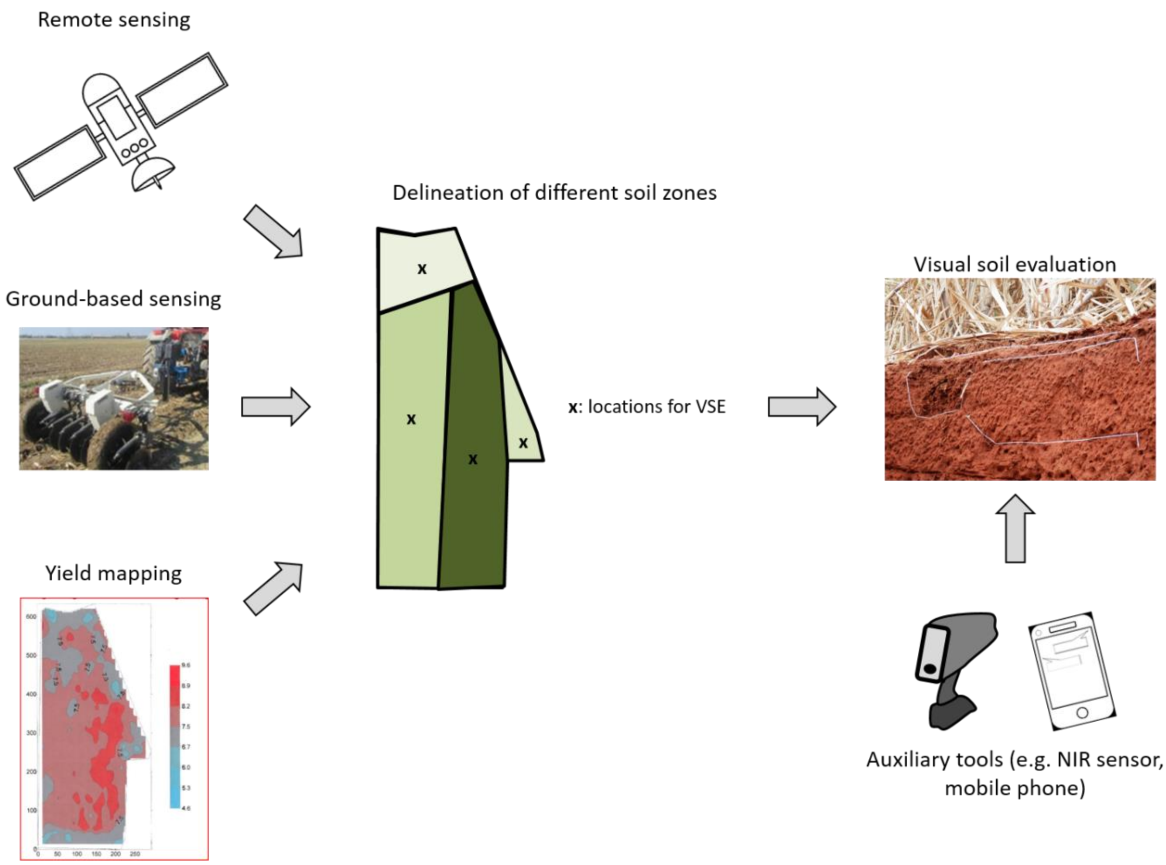

Too dry
(high soil strength,
not possible to
breakup soil by hand)
Range of suitable
water contents for
visual soil evaluation
Too wet
(soil does not
fragment)
Relative friability
Soil water matric potencial

Fig. 1.

881

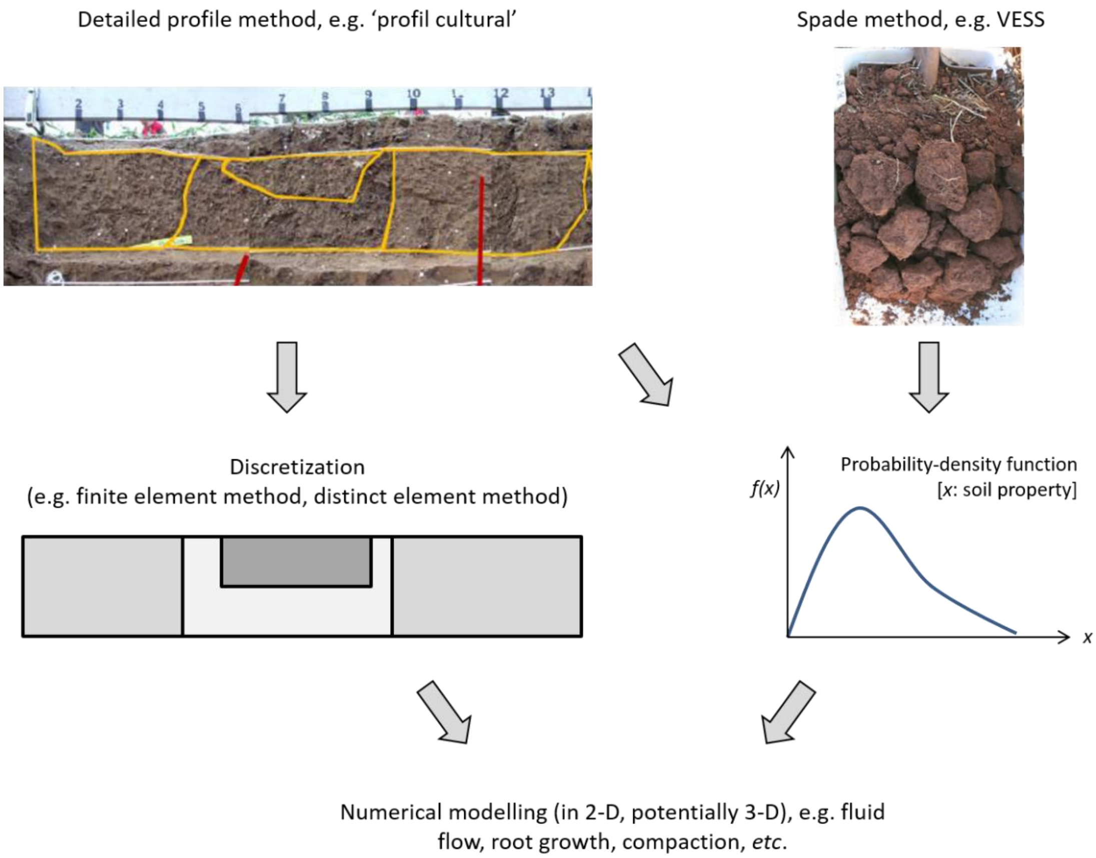


882

883 **Fig. 2.**

884

885



Detailed profile method, e.g. 'profil cultural'
Spade method, e.g. VESS
Discretization
(e.g. finite element method, distinct element method)
Probability-density function
[x: soil property]
f(x)
x
Numerical modelling (in 2-D, potentially 3-D), e.g. fluid
flow, root growth, compaction, etc.

Fig. 3.

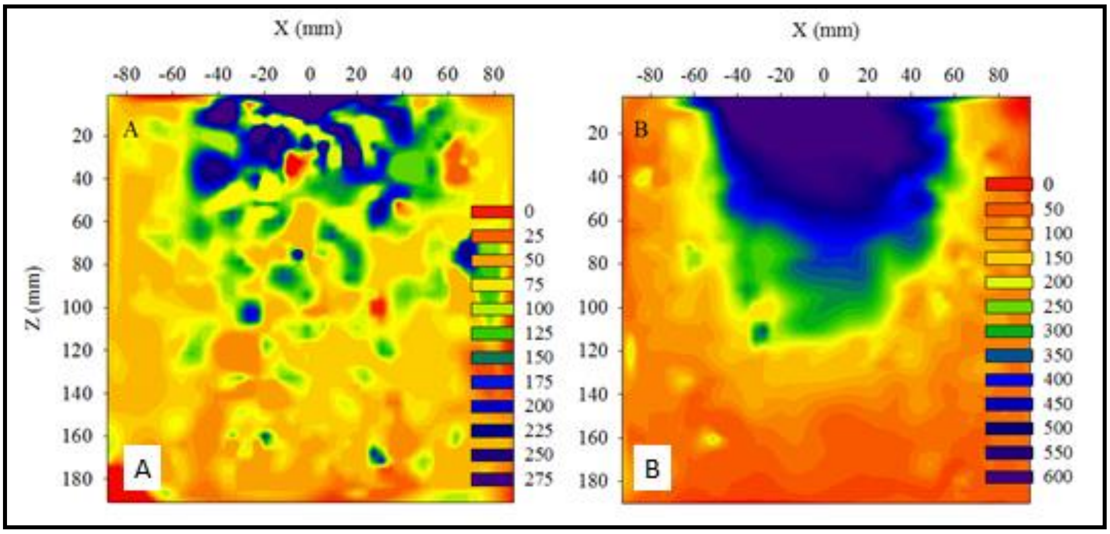

X (mm)
-80 -60 -40 -20 0 20 40 60 80
Z (mm)
20 40 60 80 100 120 140 160 180
A
0 25 50 75 100 125 150 175 200 225 250 275
X (mm)
-80 -60 -40 -20 0 20 40 60 80
20 40 60 80 100 120 140 160 180
B
0 50 100 150 200 250 300 350 400 450 500 550 600

Fig. 4.

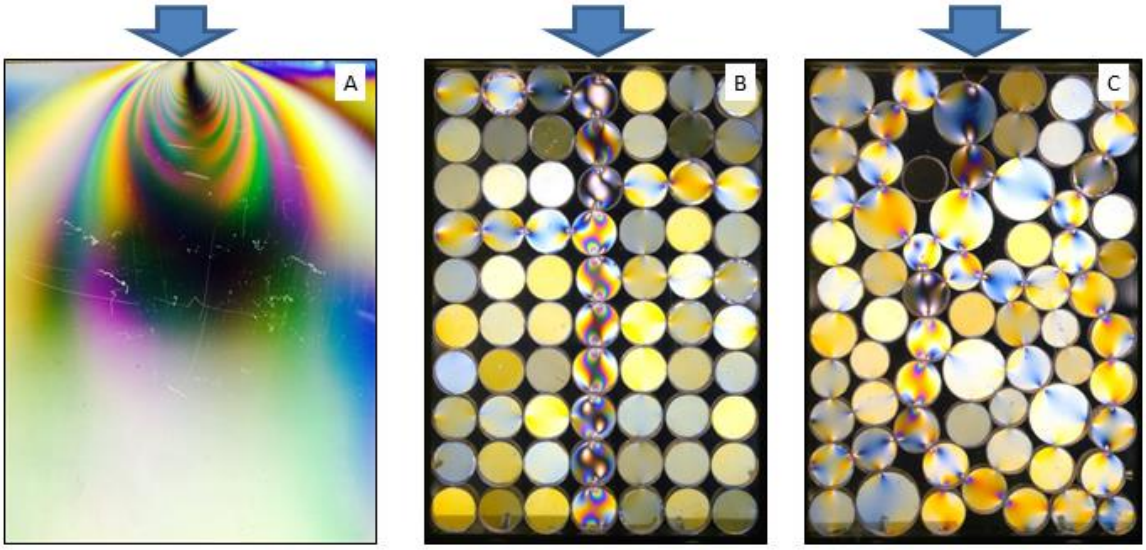


Fig. 5.